The Measurement of the Neutrino Mixing Angle, θ_{13}, and its Implications

CTP, Zewail City for Science and Technology, Egypt

April 19, 2012

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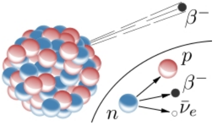
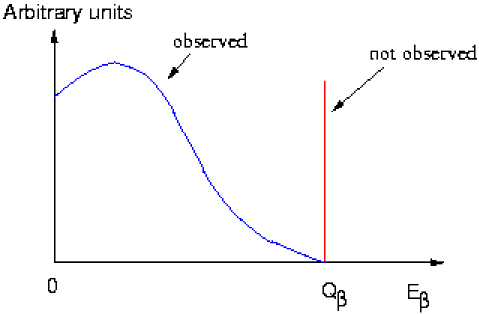
Outline

INTRODUCTION TO EXPERIMENTAL NEUTRINO PHYSICS



Before 1930's: beta decay spectrum continuous - is this energy non-conservation?



Neutrino Conception

Dec 1930: Wolfgang Pauli's letter to physicists at a workshop in Tubingen:

Wolfgang Pauli

Dear Radioactive Ladies and Gentlemen,

........., I have hit upon a desparate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons.... The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant.........
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.
Your humble servant

. W. Pauli

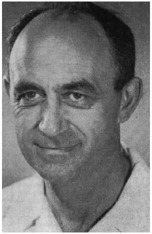
Neutrino Conception

1932: James Chadwick discovers the neutron, $\text{mass}_{\text{neutron}} = 1.0014 \times \text{mass}_{\text{proton}}$ - its too heavy - cant be Pauli's particle

James Chadwick

Neutrino Conception

Solvay Conference, Bruxelles 1933: Enrico Fermi proposes to name Pauli's particle the "neutrino".



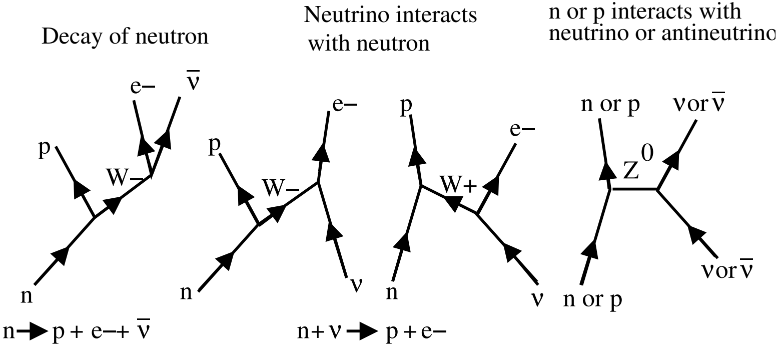
Enrico Fermi

The Theory of Weak Interactions

$\geq$ **1933:** **Fermi Glashow/Salam/Weinberg (1968) build the theory of weak interactions and beta decay**

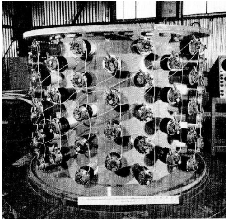
Charged current interactions

Neutral current interactions



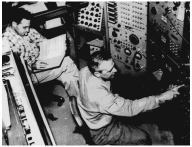
Finding Neutrinos...

1950's: Fred Reines at Los Alamos and Clyde Cowan use the Hanford nuclear reactor (1953) and the new Savannah River nuclear reactor (1955) to find neutrinos. A detector filled with water with $CdCl_2$ in solution was located 11 meters from the reactor center and 12 meters underground.



The detection sequence was as follows:

1. $\bar{\nu}_e + p \rightarrow n + e^+$
2. $e^+ + e^- \rightarrow \gamma\gamma$
3. $n +^{108} Cd \rightarrow^{109} Cd* \rightarrow^{109} Cd + \gamma$ $(\tau = 5\mu s)$.



Neutrinos first detected using a nuclear reactor!

ν: A Truly Elusive Particle!

Reines and Cowan were the first to estimate the interaction strength of neutrinos.

The cross-section is $\sigma \sim 10^{-43}\mathrm{cm}^2$ per nucleon (p,n).

$$\nu \text{ mean free path} = \frac{\text{Mass of the proton}}{\sigma \times \text{density}}$$

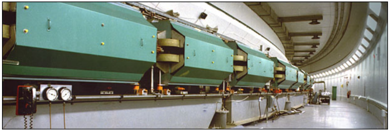
$$= \frac{1.67 \times 10^{-24}\mathrm{g}}{10^{-43}\mathrm{cm}^2 \times 11.4\mathrm{g/cm}^3} \approx 1.5 \times 10^{16}\mathrm{m} = \text{1.6 LIGHT YEARS}$$

A proton has a mean free path of 10cm in lead

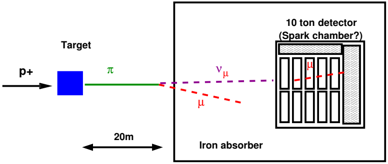
Neutrino detectors have to be MASSIVE

Neutrinos have Flavors

1962: Leon Lederman, Melvin Schwartz and Jack Steinberger use BNL's Alternating Gradient Synchrotron (AGS) to produce a beam of neutrinos using the decay $\pi \to \mu\nu_x$



The AGS



Making ν's

Result: 40 neutrino interactions recorded in the detector, 6 of the resultant particles where identified as background and 34 identified as $\mu \Rightarrow \nu_x = \nu_\mu$

The first accelerator neutrino experiment was at the AGS.

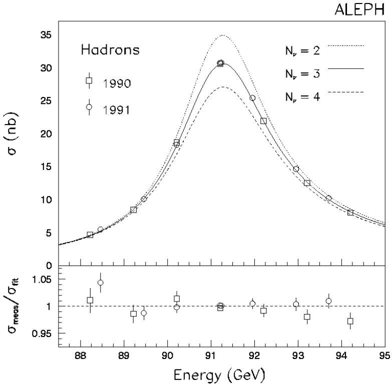
1988 Nobel prize

Number of Neutrino Flavors: Particle Colliders

1980's - 90's: The number of neutrino types is precisely determined from studies of Z^0 boson properties produced in e^+e^- colliders.

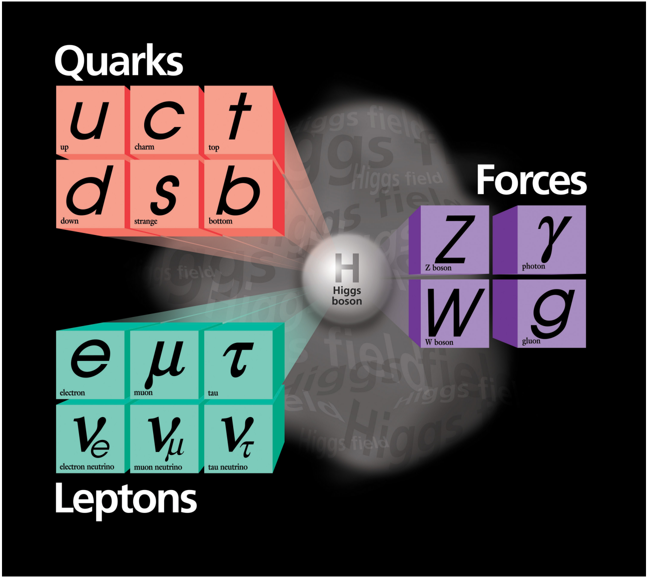
The LEP e^+e^- collider at CERN, Switzerland

The 27km LEP ring was reused to build the Large Hadron Collider



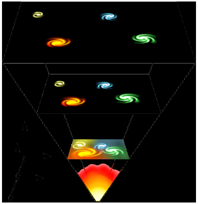
$$N_\nu = 2.984 \pm 0.008$$

The Particle Zoo



Sources of Neutrinos

Big Bang

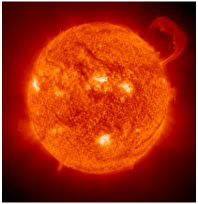


10^{-4} eV
$300/\mathrm{cm}^3$

Reactors

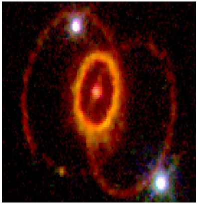
few MeV
$10^{21}/\mathrm{GW_{th}}/\mathrm{s}$

Sun



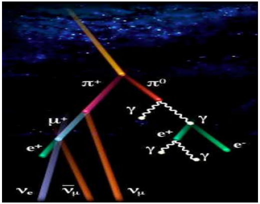
0.1-14 MeV
$10^{10}/\mathrm{cm}^2/\mathrm{s}$

SuperNova



$\sim$ 10 MeV
$10^{9}/\mathrm{cm}^2/\mathrm{s}$

Atmosphere

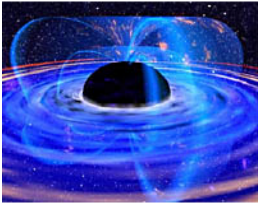


$\sim$ 1 GeV
few/cm^2/s

Accelerators

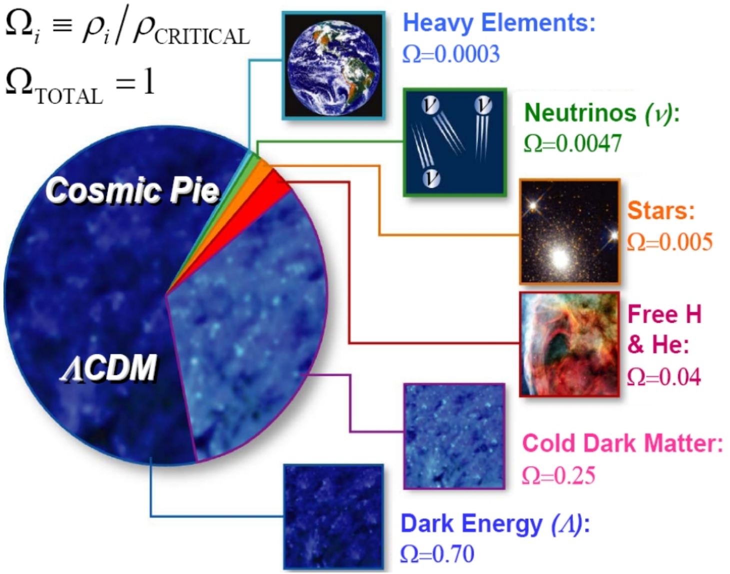
1-20 GeV
$10^{5}/\mathrm{cm}^2/\mathrm{s}$ (at 1km)

Extragalactic



TeV-PeV
varies

Neutrinos and Todays Universe - (Neutrino mass < 2 eV from beta-decay limits)



Neutrino oscillations

1957,1967: B. Pontecorvo proposes that neutrinos could oscillate:

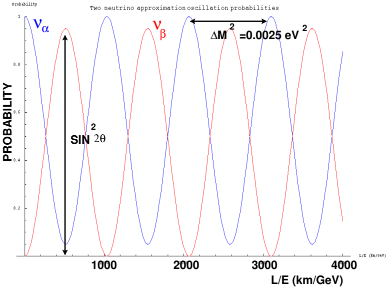
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \to \nu_b) &= \left| < \nu_b | \nu_a(t) > \right|^2 \\ &= \sin^2(\theta)\cos^2(\theta)\left|e^{-iE_2 t} - e^{-iE_1 t}\right|^2 \end{aligned}$$

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ in eV^2, L (km) and E (GeV).

Observation of oscillations implies non-zero mass eigenstates



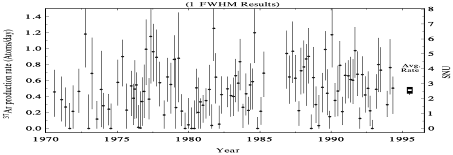
The Homestake Experiment

Ray Davis

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1. $\nu_e^{sun} + {}^{37}\mathrm{CL} \rightarrow e^- + {}^{37}\mathrm{Ar}, \ \tau({}^{37}\mathrm{Ar}) = 35$ days.
2. Number of Ar atoms $\approx$ number of ν_e^{sun} interactions.

Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU:



This is a ν_e^{sun} deficit of 69%.

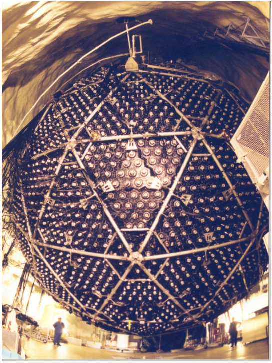
Solar ν_e disappearance $\Rightarrow$

first experimental hint of oscillations (2002 Nobel prize)

SNO Experiment: Solar ν Measurments

$1 \leftrightarrow 2$ mixing

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B\$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following ν^{sun} interactions:



$$1)\ \nu_e + d \rightarrow e^- + p + p\ (CC).$$
$$2)\ \nu_x + d \rightarrow p + n + \nu_x\ (NC).$$
$$3)\ \nu_x + e^- \rightarrow e^- + \nu_x\ (ES).$$

SNO measured:

$$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\text{stat})^{+0.12}_{-0.11}(\text{sys.}) \pm 0.05(\text{theor}) \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\text{stat})^{+0.16}_{-0.14}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$
$$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\text{stat})^{+0.46}_{-0.43}(\text{sys.}) \pm \times 10^6 \text{cm}^{-2}\text{s}^{-1}$$

All the solar ν's are there but ν_e appears as ν_x!

The Implications of 3-Neutrino Mixing

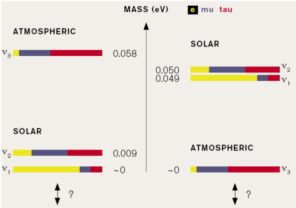
$$U_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\nu_\mu \text{ disappearance}} \underbrace{\begin{pmatrix} c_{13} & 0 & e^{i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix}}_{\nu_\mu \to \nu_e,\ \text{reactor } \bar{\nu}_e \text{ disappear}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu_e,\ \bar{\nu}_e \text{ disappear}}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

$\sin^2\theta_{13}$: Amount of ν_e in ν_3

$\tan^2\theta_{23}$: Ratio of $\frac{\nu_\mu}{\nu_\tau}$ in ν_3

$\tan^2\theta_{12}$: $\frac{\text{Amount of } \nu_e \text{ in } \nu_2}{\text{Amount of } \nu_e \text{ in } \nu_1}$



Normal Inverted

There are 3 quantum states mixing $\Rightarrow$ there is an overall phase: δ_{CP}.

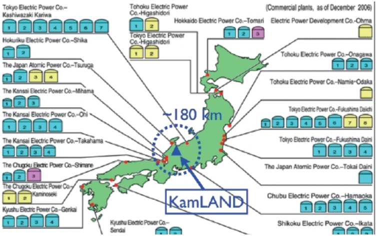
If $\delta_{\mathrm{CP}} \neq 0$ or π, charge-parity (CP) is violated and there is a $\nu/\bar{\nu}$ asymmetry.

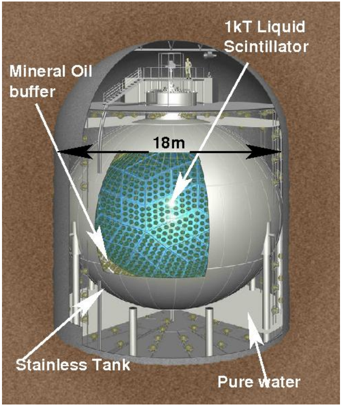
Could this explain the origin of matter?

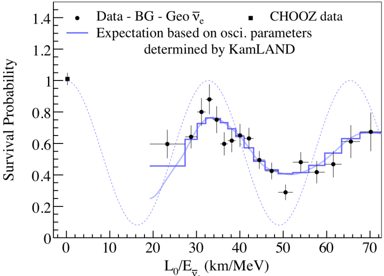
What is the value of δ_{CP}, sign(Δm^2_{31})?

KamLAND: Reactor $\bar{\nu}_e$ Measurements

$1 \leftrightarrow 2$ mixing





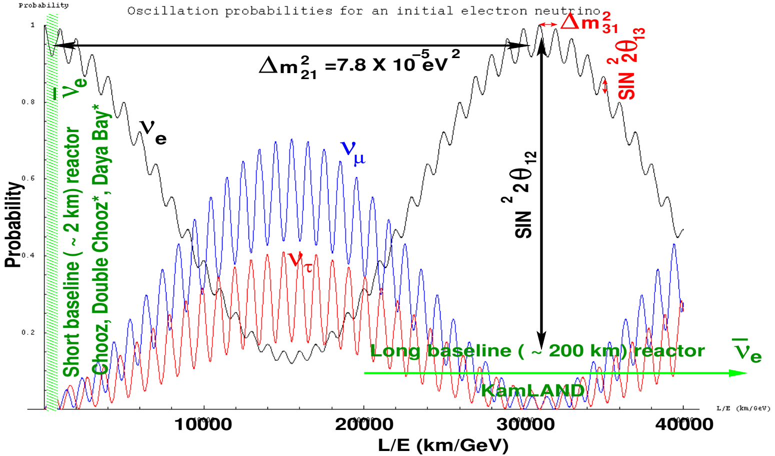


$\Leftarrow$ Clear wiggles!

$$\Delta m^2_{21} = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.47^{+0.06}_{-0.05}$$

Solar ν_e disappearance constrained $1 \rightarrow 2$ mixing. Precision from reactor $\bar{\nu}_e$ experiments :

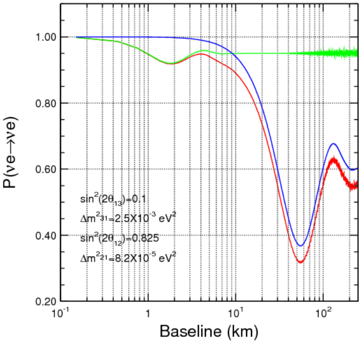


Observation of $\bar{\nu}_e$ Disappearance at Daya Bay

Short Baseline Reactor $\bar{\nu}_e$ oscillations

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

Osc prob. (integrated over E) vs distance



Unambiguous measurement of $\sin^2 2\theta_{13}$

Getting to $\sin^2 2\theta_{13} < 0.01$

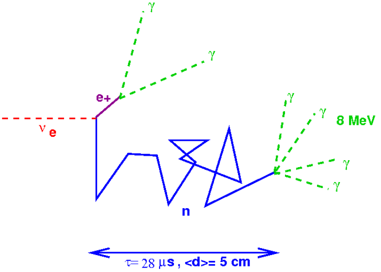
Lots of statistics: -Powerful nuclear reactors + more massive detectors

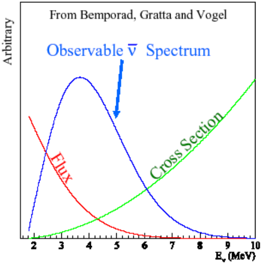
Supress cosmic backgrounds:
-Increase overburden = go deeper underground.

Reduce systematic uncertainties:
-Deploy near detectors as close as possible to reactor to minimize reactor flux uncertainties.
-Use "identical" N/F detectors to reduce near/far detector uncertainties.
-Calibration, calibration, calibration...

Detecting $\bar{\nu}_e$ using GD-loaded LS.

The active target in each detector module is liquid scintillator loaded with 0.1% Gd





The detection sequence is as follows: $\bar{\nu}_e + p \rightarrow n + e^+$ **THEN**

$e^+ + e^- \rightarrow \gamma\gamma$ (2X 0.511 MeV $+T_{e^+}$, prompt)

$n + p \rightarrow D + \gamma$ (2.2 MeV, $\tau \sim 180\mu s$, $\sigma = 0.3b$). **OR**

$n + Gd \rightarrow Gd* \rightarrow Gd + \gamma$'s (8 MeV, $\tau \sim 28\mu s$, $\sigma = 5 \times 10^4 b$).

$\Rightarrow$ delayed co-incidence of e^+ conversion and n-capture ($>$ 6 MeV)

with a specfic energy signature

The Daya Bay Reactor Complex

Reactor Specs:

Located 55km north-east of Hong Kong.

2 cores at Daya Bay site + 2 cores at Ling Ao site = 11.6 $\mathrm{GW_{th}}$

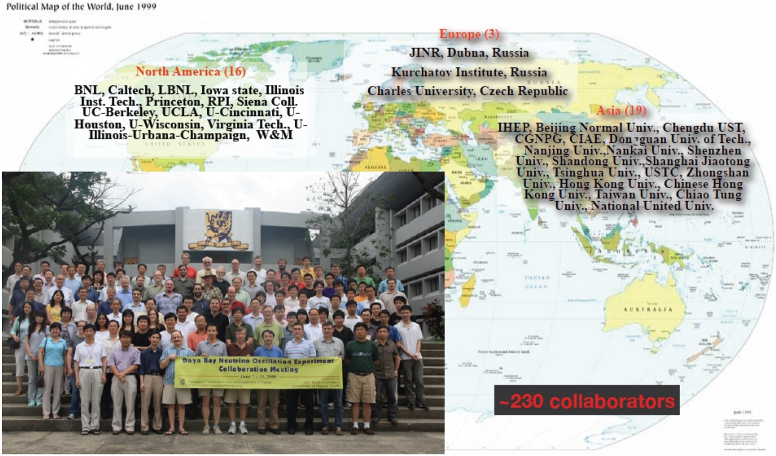
2 more cores at Ling Ao II site = 17.4 $\mathrm{GW_{th}}$ $\Rightarrow$ top five worldwide

1 $\mathrm{GW_{th}} = 2 \times 10^{20} \bar{\nu}_e/\mathrm{second}$

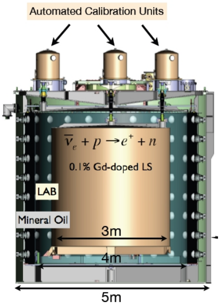
Deploy multiple near and far detectors

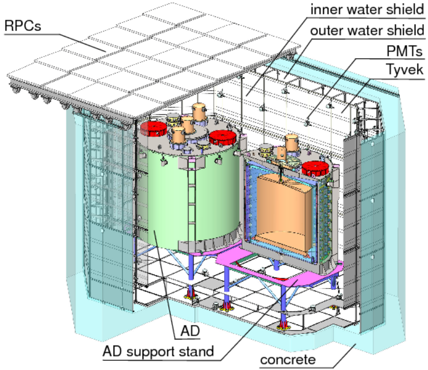
Reactor power uncertainties $< 0.1\%$

The Daya Bay Collaboration



The Daya Bay Experimental Apparatus

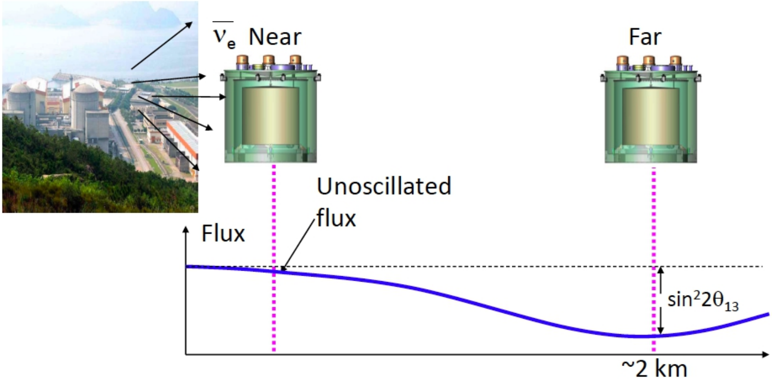




- **Multiple "identical" detectors at each site.**
- **Manual and multiple automated calibration systems per detector.**
- **Thick water shield/muon veto to reduce cosmogenic and radiation bkgds.**

	DYB	LA	Far
Event rates/20T/day	840	740	90

Daya Bay Measurement Technique



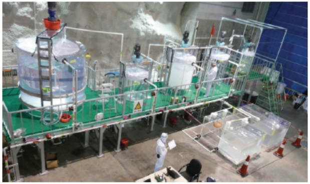
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right]$$

Far/Near Neutrino Ratio	Detector Target Mass	Distance from Reactor	Detector Efficiency	Survival Probability ($\theta 13$)

Daya Bay Measurement Goals

Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*)	Strategy
# protons	H/C ratio	0.8	< 0.1	Fill in pairs/calib
	Mass	-	< 0.3	Load cells and mass flowmeters
Detector Efficiency	Energy cuts	0.8	0.2	lower threshold/calib
	Position cuts	0.32	0.0	3-zone
	Time cuts	0.4	0.1	Common clock $\sim$ 10ns
	H/Gd ratio	1.0	0.1	fill in pairs/calib
	n multiplicity	0.5	0.05	Deeper/muon veto
	Trigger	0	0.01	Redundant triggers
	Live time	0	< 0.01	Common GPS clock
Total detector-related uncertainty		1.7%	0.38%	

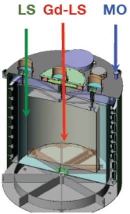
Daya Bay GD-LS Production

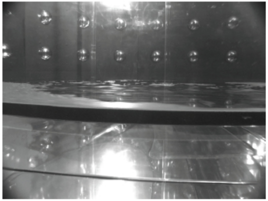


Daya Bay Liquid Scintillator Cocktail

- LAB + Gd (0.1%) + PPO (3 g/L) + bis-MSB (15 mg/L)
- more than 3 years R&D (BNL & IHEP)
- Multi-stage purifications on optical improvement and U/Th removal
- 185-ton Gd-LS + 196-ton LS production

Load cells measure 20 ton target mass to 3kg (0.015%)





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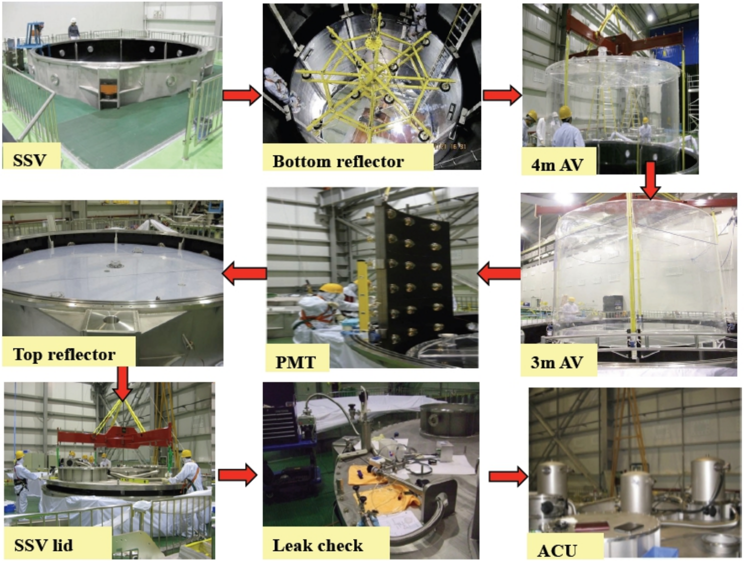
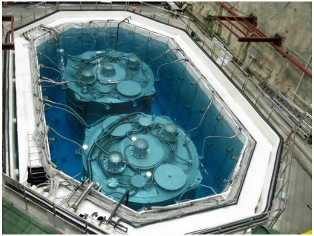
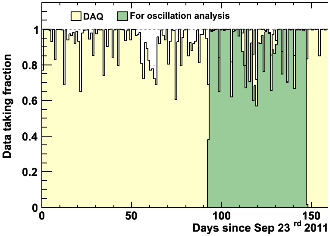
Anti-Neutrino Detector Assembly



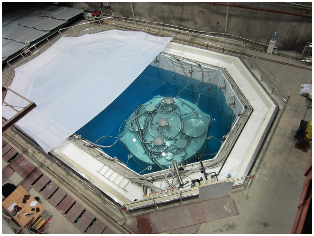
Near Halls

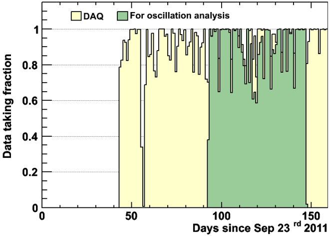
EH1 (Daya Bay) 15 Aug 2011



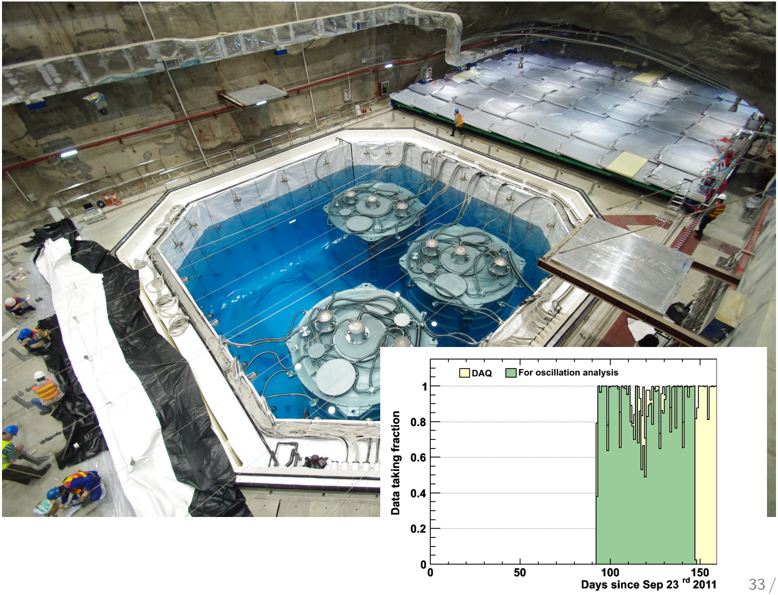


EH2 (Ling Ao I, II) 5 Nov 2011





EH3 (far site)

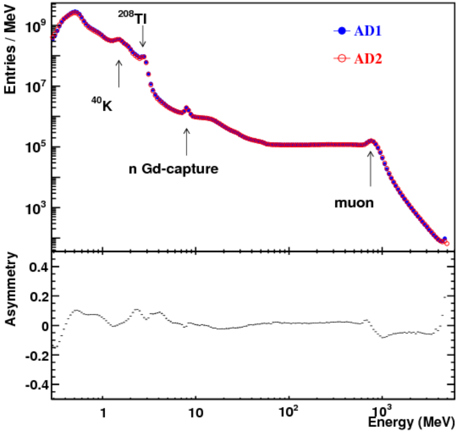

DAQ
For oscillation analysis
Data taking fraction
0
0.2
0.4
0.6
0.8
1
0
50
100
150
Days since Sep 23 rd 2011

Energy Spectrum of All Events

Using a ^{60}Co source (2.506 MeV) at center:

$\sim$ 163 photo-electrons/MeV

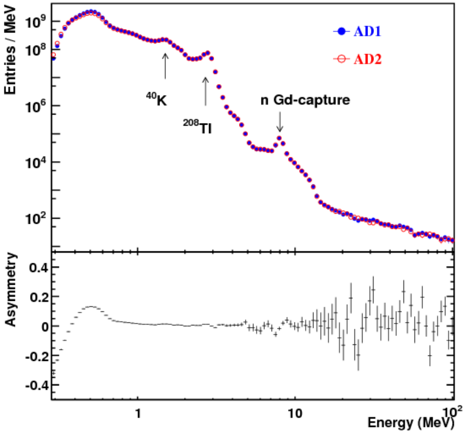
All triggered events



Energy Spectrum of All Events

Using a ^{60}Co source (2.506 MeV) at center:
$\sim$ 163 photo-electrons/MeV

Veto muons: water shield μ > 0.6ms , AD μ (> 20 MeV, > 1 ms), AD shower μ (> 2.5 GeV, > 1s



Identifying the Inverse Beta Decay Signal

Selection criteria:

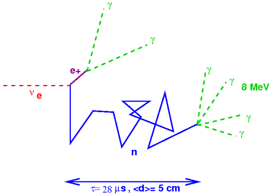
Muon veto

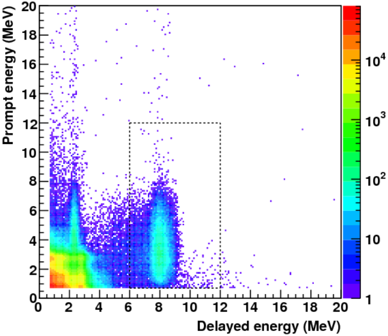
Prompt positron: $0.7 < E_{prompt} < 12$ MeV

Delayed neutron: $6 < E_{delayed} < 12$ MeV

Capture time: $1 < t_{delayed} - t_{prompt} < 200\mu s$

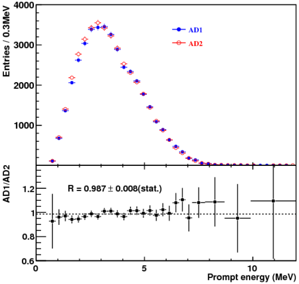
Multiplicity: < 0.7 MeV in the time range $(t_p - 200\mu s, t_d + 200\mu s)$.



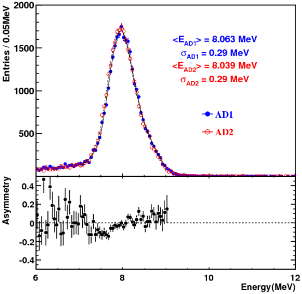


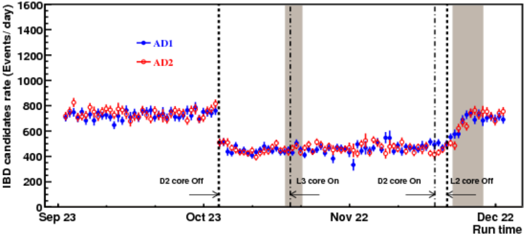
I.B.D Rates and Spectra in EH1

Positron ($\bar{\nu}_e$) signal

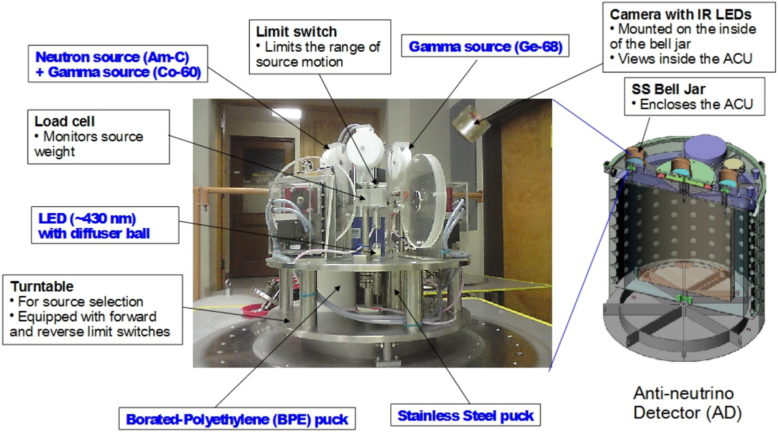


Neutron capture signal





Automated Calibration Units (ACUs)



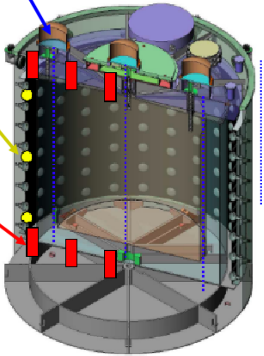
LED Calibration System

The Measurement of the Neutrino Mixing Angle, θ_{13}, and its Implications

Mary Bishai (on behalf of the Daya Bay Collaboration)

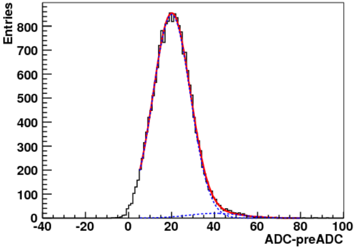
LEDs and 2” Calibration PMTs

- LEDs along three deployment axes.
- 3 fixed LEDs on detector inner wall.
- 2” PMTs on the top and bottom of detector.
- Monitor optical properties
- PMT calibration

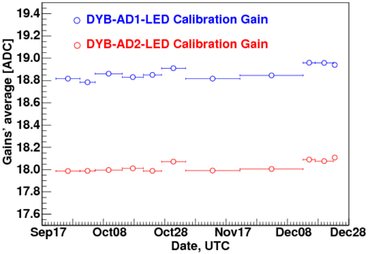


PMT Gain Calibration - EH1

Single pe peak



PMT gain stability



Gamma sources: Ge-68 & Co-60

- Ge-68 (Rate: 100 Bq, $T_{1/2}$: 270 days)

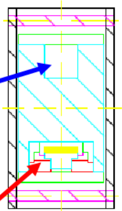
$^{68}\mathrm{Ge} \xrightarrow{EC} {}^{68}\mathrm{Ga} \xrightarrow{\beta^+} {}^{68}\mathrm{Zn}$

  - Positron threshold
  - Relative PMT detecting efficiency

- Co-60 (Rate: 150 Bq, $T_{1/2}$: 1925 days)

$^{60}\mathrm{Co} \rightarrow$ 1.173 + 1.333 MeV

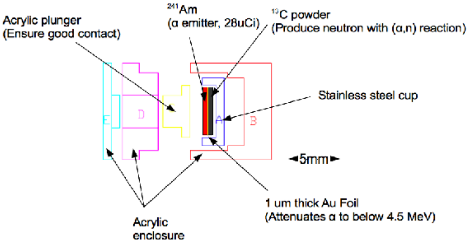
  - Energy calibration
  - Monitor light yield/attenuation



Neutron source: AmC
(Next slide)

Neutron Sources

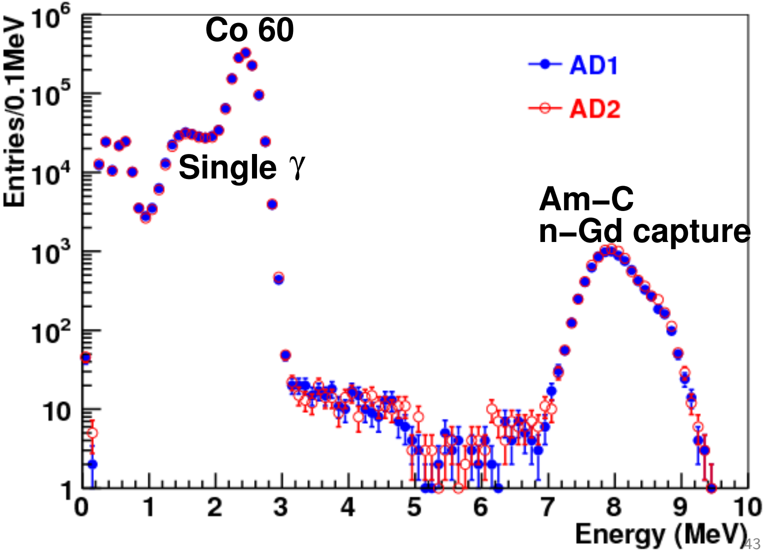
Neutron source: Am-C



^{241}Am-^{13}C (Rate: 0.5 Hz)

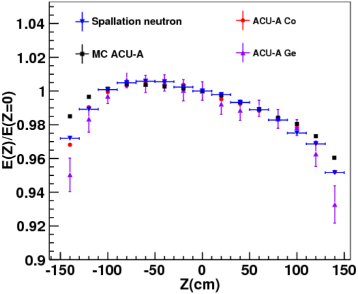
- ^{13}C (α, n) ^{16}O
- Au foil attentuate α to < 4.5 MeV, hence suppressing 6.13 MeV gamma from excited state of ^{16}O.
- Neutron energy scale

Combined Source Calibration Spectrum Am-^{1}3-C/^{60}Co EH1

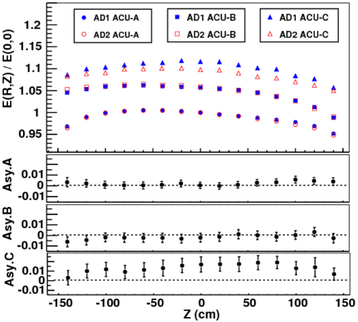


Energy Calibration - Position Non-Uniformities

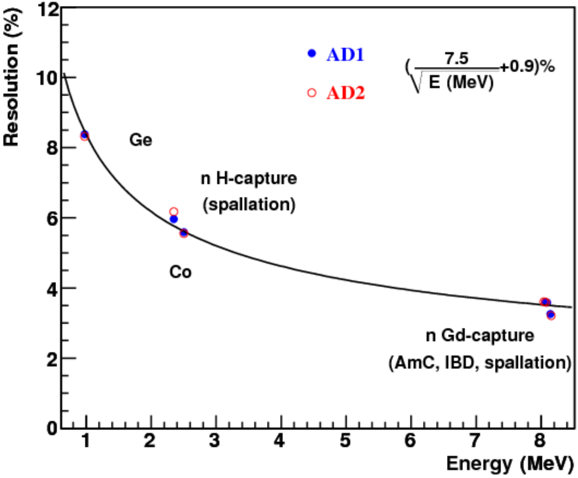
With different sources



EH1 and 2

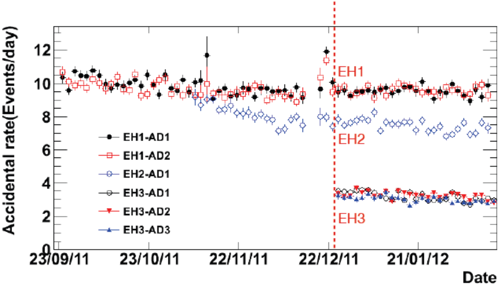


Energy Calibration - Resolution



Background Accidentals

Two uncorrelated events mimic the anti-neutrino (IBD) signals



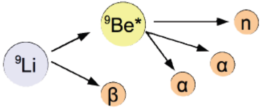
Rate and spectra can be accurately predicted from the singles data

Most delayed-like single events are from beta-decays of long-live muon spallation isotopes

B/S ratio is ~4.5% at Far site, ~1.4% at Near site

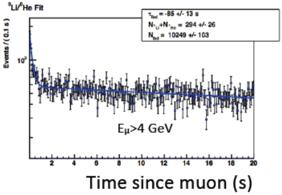
Background Muon Spallation

β-n decay:
- Prompt: β-decay
- Delayed: neutron capture



^{9}Li: $\tau_{½} = 178$ ms, Q = 13. 6 MeV

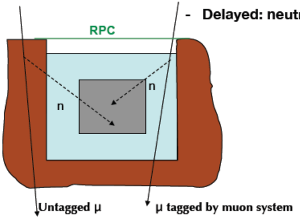
^{8}He: $\tau_{½} = 119$ ms, Q = 10.6 MeV

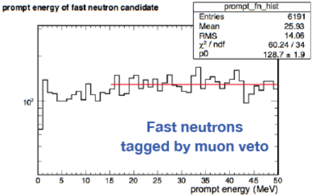


B/S: 0.2%

Fast neutron

- **Prompt: proton recoil**
- **Delayed: neutron capture**





B/S: 0.06%

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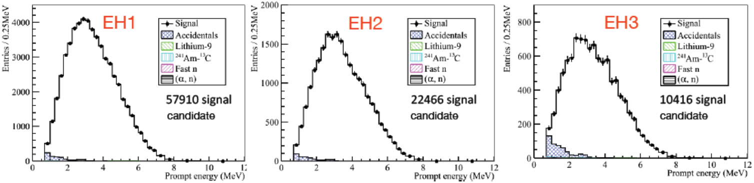
Neutrino Data in 3 Experimental Halls

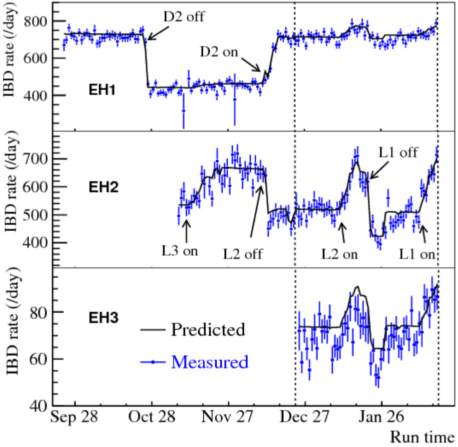
	AD1	AD2	AD3	AD4	AD5	AD6
IBD candidates	28935	28975	22466	3528	3436	3452
DAQ live time (days)	49.5530		49.4971	48.9473		
$\epsilon_\mu \cdot \epsilon_m$	0.8019	0.7989	0.8363	0.9547	0.9543	0.9538
Accidentals (per day)	9.82±0.06	9.88±0.06	7.67±0.05	3.29 ±0.03	3.33 ± 0.03	3.12 ±0.03
Fast-neutron (per day)	0.84±0.28	0.84±0.28	0.74±0.44	0.04±0.04	0.04±0.04	0.04±0.04
^{9}Li/^{8}He (per AD per day)	3.1±1.6		1.8±1.1	0.16±0.11		
Am-C correlated (per AD per day)	0.2±0.2					
^{13}C(α, n)^{16}O background (per day)	0.04±0.02	0.04±0.02	0.035±0.02	0.03±0.02	0.03±0.02	0.03±0.02
IBD rate (per day)	714.17±4.58	717.86± 4.60	532.29±3.82	71.78 ± 1.29	69.80±1.28	70.39±1.28

High statistics anti-neutrino spectra



Daily I.B.D. Rates

No-oscillation predictions are obtained using reactor flux analysis and detector simulations and compared to the observed I.B.D. rate:



Systematic Uncertainties

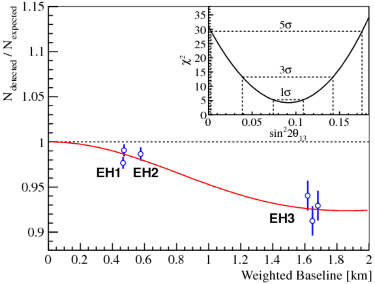
Detector

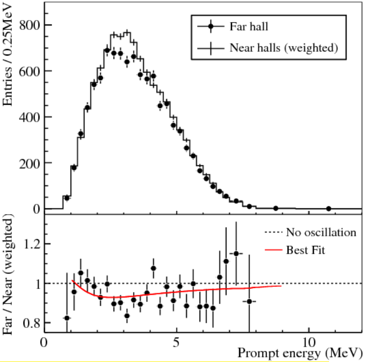
	Efficiency	Correlated	Uncorrelated
Target Protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	90.9%	0.6%	0.12%
Prompt energy cut	99.88%	0.10%	0.01%
Multiplicity cut		0.02%	<0.01%
Capture time cut	98.6%	0.12%	0.01%
Gd capture ratio	83.8%	0.8%	<0.1%
Spill-in	105.0%	1.5%	0.02%
Livetime	100.0%	0.002%	<0.01%
Combined	78.8%	1.9%	0.2%

Reactor

Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
IBD reaction/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Measurement of $\sin^2 2\theta_{13}$: March 8, 2012





Rate only: $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

Summary and Conclusions

Mary Bishai (on behalf of the Daya Bay Collaboration)

- **The Daya Bay experiment has measured a non-zero value for the neutrino mixing angle θ_{13} with a significance of 5.2 σ. This is the first observation of a non-zero θ_{13}.**
- **A rate only analysis finds:**

  Rate only: $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
- **On April 12, 2012 the RENO experiment confirmed the Daya Bay result and measured:**

  Rate only: $\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$
- **The stage is now set for measurement of the CP-violating phase and the hunt for CP violation in the neutrino sector using $\nu_\mu \rightarrow \nu_e$ oscillations with the next generation of accelerator long baseline neutrino experiments.**

THANK YOU